PRODUCTION OF ENERGETIC PHOTONS VIA EXCITATION OF THE Δ RESONANCE IN HEAVY ION COLLISIONS

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The photon production cross sections is calculated for heavy ion collision with beam energies between 75 and 200 MeV/nucleon. The decay of the Δ resonance should dominate the photon spectrum above a photon energy of 200 MeV for the high beam energy. At the lower beam energies, the Δ contribution is obscured by photons originating from np bremsstrahlung.

During the last five years, the study of high energy photon production ($E_\gamma > 50$ MeV) from intermediate energy ($20 < E_{beam}/A < 100$ MeV) heavy ion collisions has generated increasing interest. Since the early data of Beard et al. [1] and Grosse et al. [2], many experimental groups have conducted systematic studies of high energy photon production [3–6].

It now seems to be established that these photons are mainly bremsstrahlung from individual neutron–proton collisions during the course of the heavy ion collision. This was originally proposed by Nifenecker and Bondorf [7]. However, their model required on the order of 20 collisions per nucleon to reproduce the data. Using the nuclear Boltzmann–Uehling–Uhlenbeck (BUU) transport theory and the assumption of the elementary process being $p+n \to p+n+\gamma$, we were able to reproduce the experimental data between 20 and 50 MeV/nucleon [8]. Similar results were obtained later by Aichelin and Ko [9] and by Heuer et al. [10]. Our results fall short of the data [6] at the higher energy of $E_{beam} = 84$ MeV/nucleon. We will return to this point later.

Recently, Prakash et al. [11] suggested using detailed balance to obtain photon emission rate from the measured photoabsorption cross sections of nuclei. Since photoabsorption is measured with ground state nuclei and photons in intermediate energy heavy ion collisions are emitted from a highly excited nuclear system, the authors of ref. [11] make an extrapolation from the ground state absorption to the photoabsorption on hot nuclei. Furthermore, this approach assumes statistical equilibrium, which is problematic. The authors of ref. [11] find that the gamma production cross section in heavy ion collisions is enhanced by about a factor of 10 for photon energies of ≈ 200 MeV in intermediate energy heavy ion collisions, due to the enhanced photon absorption around the Δ resonance region. In their calculation this enhancement should be visible as a hump on top of the otherwise exponentially falling bremsstrahlung photon spectrum.

Measuring the high energy photon spectrum, the MSU group has not seen the expected change in shape of the photon spectrum due to the excitation of the Δ resonance in the reaction of $^{14}N + Zn$ at a beam energy per nucleon of 75 MeV [12]. It is therefore clear that more sophisticated models are needed.

In this letter, we report on the results of a study using the Boltzmann–Uehling–Uhlenbeck (BUU) transport equation. We have performed calculations for symmetric heavy ion collisions and beam energies per nucleon between 75 and 200 MeV by solving the BUU equation for the phase space distribution function of nucleons $f(\boldsymbol{r}, \boldsymbol{p}, t)$. The numerical details of solving this equation are described in ref. [8], except for the production and decay of the Δ's which we treat differently.

We treat the production of the Δ resonance in nucleon–nucleon collisions using the experimental cross sections for pion production [13]. We follow the ansatz of Mandelstam [14] and assume that pions are exclusively produced via the $\Delta(1232)$ resonance for nucleon–nucleon center-of-mass energies $\lessapprox 2.2$ GeV.

We neglect the s-wave contribution to the pion production, and this deserves some discussion. following Richard-Serre et al. [15] the cross section for the process $p+p\to\pi+d$ can be expressed as

$$\sigma_\pi = (0.18\pm0.02)\eta + (0.95\pm0.15)\eta^3\,, \tag{1}$$

where σ_π is given in units of mb and η is the pion momentum in the CM system in units of M_π. Here, the first term is the s-wave contribution and the second term is the resonance contribution. Very near the threshold, the s-wave contribution clearly dominates. However, at a pion kinetic energy $E_1^\pi = 12.7$ MeV in the CM system both contributions are equal in magnitude, and at an energy $E_2^\pi = 20.6$ MeV the energy integrated cross sections are equal, $\int \sigma_s \mathrm{d}E = \int \sigma_\Delta \mathrm{d}E$. Attributing all of the pion yield below these kinetic energies to the s-wave contribution, we obtain reductions in our calculated Δ–photon spectra of 16% and 31% for $E^{\mathrm{p}}i_1$ and $E^{\mathrm{p}}i_2$, respectively, for the beam energy of 75 MeV/nucleon. For 200 MeV/nucleon, the reductions are 0.7% and 1.8%, respectively.

The shape of the Δ resonance mass distribution is parametrized following Kitazoe et al. [16] as

$$p(M_\Delta, \sqrt{s}) = \frac{\frac{1}{4}\Gamma^2(q)}{(M_\Delta - M_0)^2 + \frac{1}{4}\Gamma^2(q)}\,\theta(\sqrt{s} - M_\Delta - M_\mathrm{N})\,. \tag{2}$$

Here $M_0 = 1232$ MeV is the mass of the peak of the resonance, M_N is the nucleon mass, and $\sqrt{s}$ is the total center-of-mass energy in a given nucleon–nucleon collision. The cutoff involving the θ-function in eq. (2) is required to enforce energy conservation in the production process. The width $\Gamma(q)$ is parametrized as

$$\Gamma(q) = \frac{0.47 q^3}{[1 + 0.6(q/M_\pi)^2] M_\pi^2}\,, \tag{3}$$

where q is the momentum of the Δ in the N–Δ center-of-mass frame. We assume that the Δ is produced isotropically in this frame.

The branching ratio for $\Delta\to N+\pi$ is greater than 99%. However, the Δ resonance has also a branching ratio [17] of 0.6% for $\Delta\to N+\gamma$. In our calculation we have assumed that this branching ratio is independent of the energy of the Δ. Of course, this decay channel is only open to the Δ^0 and Δ^+ charge states, whereas it is forbidden for the Δ^- and Δ^{++} charge states.

In the decay $\Delta\to N+\gamma$ the absolute magnitude of the momentum of the photon in the Δ rest frame is given by

$$p_\gamma = \frac{M_\Delta^2 - M_\mathrm{N}^2}{2M_\Delta}\,, \tag{4}$$

where M_N is the mass of the nucleon, and M_Δ is distributed according to eq. (2). We assume that the Δ decays isotropically in its rest frame and perform a Monte Carlo integration over all possible momenta for the outgoing photon and nucleon.

In this way it is possible to calculate the production of photons via the excitation of the Δ resonance in a similar way as we have done for the production of π^0's [18]. In ref. [18], we reproduced the absolute cross section of π^0 production for beam energies up to 84 MeV/nucleon, using the same parametrization of the Δ production. We thus have some confidence in our treatment of the Δ physics.

In fig. 1 we show the double differential photon spectrum for high energy photons produced via the excitation of the Δ resonance in collisions of two ^{12}C nuclei at a beam energy per nucleon of 200 MeV. Displayed are the energy spectra for the intervals (from

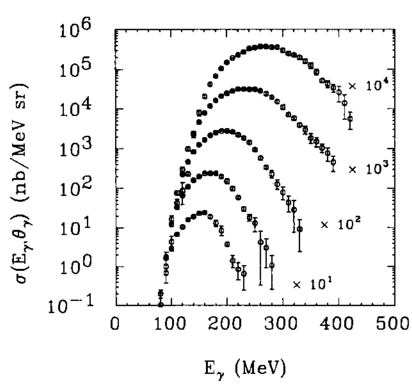

Fig. 1. Calculated double differential photon cross section from the decay $\Delta\to N+\gamma$ for the reaction $^{12}C+^{12}C$ at a beam energy of 200 MeV per nucleon in the laboratory system. The angular bins are (from top to bottom) $\cos\theta_{\mathrm{lab}} = [1, 0.75]$, $[0.75, 0.25]$, $[0.25, -0.25]$, $[-0.25, -0.75]$, and $[-0.75, -1]$.

top to bottom) $\cos\theta_{lab}=[1, 0.75]$, $[0.75, 0.25]$, $[0.25, -0.25]$, $[-0.25, -0.75]$, and $[-0.75, -1]$ in the laboratory system. The spectra for different angles show maxima between photon energies of 150 and 250 MeV for the different angular bins. The angular dependence of the maximum energies as well as the angular dependence of the steepness of the high energy tails of the spectra is due to the transformation of the spectra from the center-of-mass to the laboratory system. The error bars given in fig. 1 are statistical error bars only and were compiled from the simulation of 500 collisions of two ^{12}C nuclei. The fact that photon energies in excess of 200 MeV (the beam energy) are produced is mainly due to the Fermi motion of the nucleons inside the nuclei.

In 100 central collisions between two ^{12}C nuclei we find that on the average 0.018 ± 0.04 Δ's are produced at $E_{beam}=75$ MeV/nucleon. Taking absorption into account [18], this leads to 0.003 π^0's and $\approx 10^{-4}$ photons due to the decay of the Δ into neutral pions and photons. For $E_{beam}=200$ MeV/nucleon the number of produced Δ resonances increases to 3.7 ± 0.2, resulting in 0.6 π^0's and 0.02 high energy gamma rays.

We next compare the photon yield from Δ's with other sources of photons. In fig. 2, the photon spectrum from Δ's is shown together with the bremsstrahlung spectrum and the yield from π^0 decays, for collisions of $^{12}C+{}^{12}C$ at $E_{beam}=75$ MeV/nucleon and a laboratory angle of 90°.

The lower energy photons (30 MeV$<E_\gamma<$100 MeV) were underpredicted [8] by about a factor of

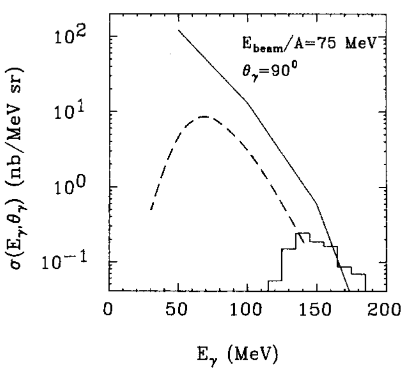

Fig. 2. Comparison of the contributions of pn bremsstrahlung (solid line), decay of the π^0 (dashed line), and one-photon decay of the Δ resonance (histogram) to the photon spectrum. Calculations were done for the system $^{12}C+{}^{12}C$ in the laboratory system.

2–3, which is probably due to the use of a classical radiation formula for the elementary bremsstrahlung production amplitude. More sophisticated models [19] tend to predict a higher photon yield due to exchange currents and magnetic amplitudes. Thus the curve representing the bremsstrahlung contribution (solid line) in fig. 2 should be viewed as a lower bound on the direct $n+p \to n+p+\gamma$ contribution. The histogram shows the calculated photon spectrum from the decay of the Δ resonance. The dashed line shows the photons produced by the decay $\pi^0 \to 2\gamma$; it is in good agreement with a Monte Carlo calculation simulating the two-photon decay spectrum from existing π^0 data [12].

It is clear from fig. 2 that the contribution of the Δ resonance decay should not show up as a strong enhancement of the exponentially falling spectrum as predicted in ref. [11]. This finding is in agreement with the results of the first experiment performed at MSU-NSCL's new K800 cyclotron. Here the yield of high energy photons was measured for the reaction 75 MeV/nucleon $^{14}N+Zn$, and no enhancement of the spectrum over the exponential fall-off was found [12]. Even though we have calculated for a much lighter system, our findings should also hold in this heavier case. This is because both the bremsstrahlung and the Δ decay photons are produced in nucleon–nucleon collisions in our model. Therefore they should exhibit the same scaling behaviour with target and projectile mass.

For higher beam energies, it is certainly not valid to use the classical bremsstrahlung cross section formula any more. But it is possible to calculate the expected contribution of the decay of the Δ resonance and compare it to the expected spectrum of photons from the π^0 decay. the cross sections obtained for this process are still reliable, because we only use the experimentally measured elementary production cross sections, and because we found good agreement between the calculated and the experimental π^0 spectra for all beam energies considered [18].

In fig. 3 we calculate the spectrum of the high energy photons originating from the decay of the Δ resonance to the photons from the decay of the π^0 meson for the reaction $^{12}C+{}^{12}C$ at a beam energy per nucleon of 200 MeV. For photon energies above 200 MeV, both contributions are comparable in magnitude. Since it is known [20] that for this energy the production of π^0 becomes dominant over the produc-

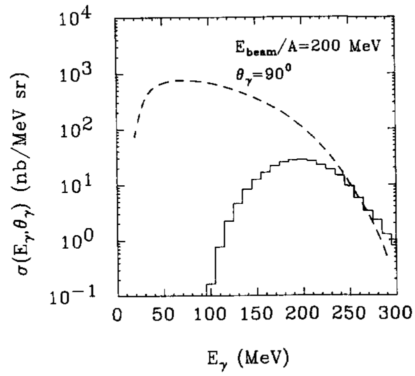

Fig. 3. Comparison of the contributions from the decay of the π^0 (dashed line) and the one-photon decay of the Δ resonance (histogram) to the photon spectrum at a beam energy per nucleon of 200 MeV. Calculations were done for the system $^{12}C+^{12}C$ in the laboratory system.

tion of bremsstrahlung photons, the contribution of the decay of the Δ resonance should become visible in the high energy photon spectrum, provided an effective suppression of the background due to the π^0 decay photons is achieved. To obtain this suppression, anti-coincidence methods using large granulated photon detection systems are needed.

In contrast to pions, photons are practically not subject to reabsorption inside the nuclear medium. The information gained from the direct decay photons of the delta resonance could thus provide us with valuable insight into the propagation of excited nucleonic states inside nuclear matter. One possible effect that might be investigated is a possible change in the width of the Δ mass peak. This could come about due to a change in lifetime of the Δ due to the effect of the Pauli exclusion principle on the nucleon in the final state.

In summary, we have calculated the high energy photon spectrum resulting from the one-photon decay of the Δ resonance. To do this we have used the semi-classical Boltzmann–Uehling–Uhlenbeck transport theory and the assumption that the branching ratio for this decay is 0.6%, independent of energy. We find that this contribution to the high energy photon spectrum should not be visible at a beam energy per nucleon of 75 MeV; but it should be measurable for a beam energy of 200 MeV.

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References

[1] K. Beard, W. Benenson, C. Bloch, E. Kashy, J. Stevenson, D.J. Morissey, J. Vanderplicht, B. Sherrill and J.S. Winfield, Phys. Rev. C 32 (1985) 1111.
[2] E. Grosse, P. Grimm, H. Heckwolf, W.F.J. Müller, H. Noll, A. Oskarsson and H. Stelzer, Europhys. Lett. 2 (1986) 9.
[3] N. Alamanos, P. Braun-Munzinger, R.H. Freifelder, P. Paul, J. Stachel, T.C. Awes, R.L. Fergusson, F.E. Obenshain, F. Plasil and G.R. Young, Phys. Lett. B 173 (1986) 392.
[4] J. Stevenson, K.B. Beard, W. Benenson, J. Clayton, E. Kashy, A. Lampis, D.J. Morrissey, M. Samuel, R.J. Smith, C.L. Tam and J.S. Winfield, Phys. Rev. Lett. 57 (1986) 555.
[5] R. Hingmann, W. Kühn, V. Metag, R. Mühlhans, R. Novotny, A. Ruckelshausen, W. Cassing, H. Emling, R. Kulessa, H.J. Wollersheim, B. Hass, J.P. Vivien, A. Boullay, H. Delagrange, H. Doubre, C. Grégoire and Y. Schutz, Phys. Rev. Lett. 58 (1987) 759.
[6] M. Kwato Njock, M. Maurel, E. Monnand, H. Nifenecker, J.A. Pinston, F. Schussler, D. Barneoud and Y. Schutz, Nucl. Phys. A 482 (1988) 489c, and references therein.
[7] H. Nifenecker and J.P. Bondorf, Nucl. Phys. A 442 (1985) 478.
[8] W. Bauer, G.F. Bertsch, W. Cassing and U. Mosel, Phys. Rev. C 34 (1986) 2127;
T.S. Biro, K. Niita, A.L. DePaoli, W. Bauer, W. Cassing and U. Mosel, Nucl. Phys. A 471 (1987) 604;
K. Niita, A.L. DePaoli, W. Bauer, T.S. Biro, W. Cassing and U. Mosel, Nucl. Phys. A 482 (1988) 525c.
[9] J. Aichelin and C.M. Ko, Phys. Rev. C 35 (1987) 1976.
[10] R. Heuer, B. Müller, H. Söcker and W. Greiner, Z. Phys. A 330 (1988) 315.
[11] M. Prakash, P. Braun-Munzinger, J. Stachel and N. Alamanos, Phys. Rev. C 37 (1988) 1959.
[12] J. Clayton and J. Stevenson, private communication.
[13] B.J. VerWest and R.A. Arndt, Phys. Rev. C 25 (1982) 1979;
W.O. Lock and D.F. Measday, Intemediate energy nuclear physics (Methuen, London, 1970).
[14] S. Mandelstam, Proc. R. Soc. A 244 (1958) 491.
[15] C. Richard-Serre, W. Hirt, D.F. Measday, E.G. Michaelis, M.J.M. Saltmarch and P. Skarek, Nucl. Phys. B 20 (1970) 413.
[16] Y. Kitazoe, M. Sano, H. Toki and S. Nagamiya, Phys. Lett. B 166 (1986) 35.
[17] Particle Data Group, R.L. Kelly et al., Review of particle properties, Rev. Mod. Phys. 52 (1980) S1.
[18] W. Bauer, Phys. Rev. C (July 1989) to be published.
[19] D. Neuhauser and S.E. Koonin, Nucl. Phys. A 462 (1987) 163.
K. Nakayama, Phys. Rev. C, in print;
K. Nakayama and G.F. Bertsch, submitted to Phys. Rev. C.
[20] V. Metag, Nucl. Phys. A 488 (1988) 483c.